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Recreational Water Quality Analyses of the Colorado River Corridor in Grand Canyon

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We intensively examined the recreational water quality of the Colorado River and 26 tributaries in Grand Canyon National Park over four consecutive summers. Highly ephemeral precipitation cycles and arid watershed hydrologies were the principal factors influencing water quality. Fecal coliforms (FC) in the river and in most tributaries were $\leq$10 FC 100 ml^{-1} and $\leq$20 FC 100 ml^{-1}, respectively, during drought cycles. During rainfall cycles, FC densities were highly variable and often exceeded recreational contact standards. FC were not found to vary significantly in response to diurnal fluctuations in river stage height which resulted from hydroelectric stream flow regulation. River and tributary bottom sediments harbored FC in densities averaging 10 to 100 times those in the overlying waters. Sediment FC densities were not found to be reliable indicators of overlying water quality when storm flow and nonstorm flow periods were compared.

Visitor reliance on available surface waters for drinking, cooking, hygiene, and recreational contact purposes is typical of wilderness recreation in the Western United States. The microbiological quality of backcountry waters is rarely monitored, however, because of logistical difficulties associated with examining these remote resources. Data for some remote natural areas have demonstrated that fecal contamination can be expected in the pristine waters associated with backcountry settings. In studies designed to examine waters that represent "natural" conditions, coliforms, fecal coliforms (FC), and enterococci were isolated from streams draining two forested mountain watersheds in Montana, one open and the other closed to public use (6, 32, 40). Presumably, wildlife was the principal source of fecal contamination. In Colorado, *Salmonella* species and *Arizona* species have been isolated from a high mountain stream in the Cache la Poudre River basin (13). Coliforms and fecal streptococci (FS) have also been isolated from selected mountain streams and lakes in Grand Teton National Park, Wyoming (33). In another small Wyoming stream draining a natural area, concentrations of total coliforms (TC), FC, and enterococci were found to vary seasonally (31). Although the preceding studies were not designed to determine the suitability of water for recreational contact or potability, the data reported indicated that the waters studied met full-body contact standards (3, 13a) but not standards for potable waters (public law 95-523).

The above studies examined small mountain streams or lakes in humid environments. Within the arid Southwestern United States, highly ephemeral precipitation patterns and watershed hydrologies are significantly different than those found in humid mountain regions. Because wild-land surface water quality is an integration of watershed inputs, stream water quality in arid environments and the processes which determine it may differ significantly from those of humid mountain regions. To examine recreational water quality in an arid environment, we studied the Colorado River drainage within Grand Canyon National Park, beginning in 1978.

The Colorado River drainage basin within Grand Canyon includes over 20 perennial and thousands of ephemeral tributaries. As one of the premiere wilderness recreation areas in North America, Grand Canyon is visited annually by ca. 15,000 river runners and tens of thousands of backpackers (36). Before 1978, the degree to which the Colorado River and its tributaries were contaminated with enteric organisms was undetermined. Concern for waterborne disease in Grand Canyon first emerged in 1972, when an outbreak of shigellosis occurred among river runners. Investigators from the Centers for Disease Control found FC densities of $\geq$10 FC 100 ml^{-1} in 19 of 26 spot samples collected from the Colorado River and selected tributaries (25). The most probable cause of the outbreak was attributed to person-to-person contact among river runners. A second shigellosis outbreak occurred in 1979. A Centers for Disease Control investigation again implicated person-to-person contact as the principal mode of transmission; waterborne transmission could not be ruled out, however, in either outbreak (37). The 1972 disease outbreak led to a study of the sanitary significance of burying human feces in Colorado River beaches (29). That study revealed a high level of beach contamination, resulting in a National Park Service (NPS) regulation requiring river parties to remove their feces from the canyon in sealed portable toilets.

Studies were conducted to determine the recreational water quality of the Colorado River and the confluent reaches of 26 tributaries in Grand Canyon. Specifically, this research established a profile of water quality for the river corridor, examined the influences of ephemeral precipitation and arid land hydrology on backcountry water quality, and determined the impact hydroelectric regulation of the river has on water quality. These investigations required determination of indicator bacteria densities in the waters and bottom sediments of the river and tributaries. Although previous work on backcountry waters have not examined sediments, sediments have figured importantly in the overall water quality of a wide range of aquatic environments (1, 4, 16, 17, 23, 38). Sediments were included here to determine their role in backcountry water quality.

MATERIALS AND METHODS

Study site. Field work was conducted on the Colorado River from Lee's Ferry to Diamond Creek (362 km) and 26 tributaries within this reach (Fig. 1). Colorado River stream flow is controlled by hydroelectric releases from Lake Powell (65,000 ha), 22.5 km upstream of Lee's Ferry.

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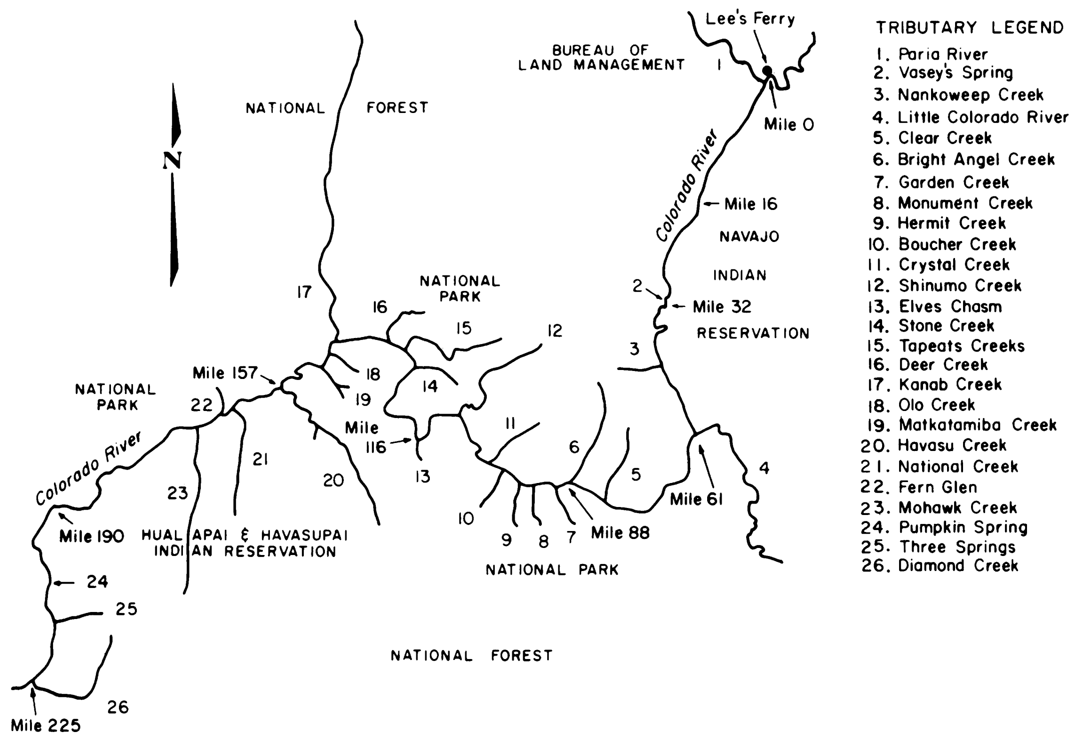

FIG. 1. Colorado River and tributaries in Grand Canyon.

Summer flows typically resemble a daily tide, as releases fluctuate somewhere between extremes of 85 and 935 $m^3 s^{-1}$. In contrast to the river, tributary flow is generally insignificant (<0.28 $m^3 s^{-1}$). Flash floods can increase tributary flows dramatically (35). Flood events in most perennial side streams and ephemeral washes are of short duration, owing to the localized nature of thunderstorms and limited basin size (3,500 km^2 collectively). The expansive watersheds of the Paria and Little Colorado Rivers and Kanab Creek (68,000 km^2 collectively) can, however, generate storm flow for days to months (35).

To establish a profile of water quality in Grand Canyon, access to the river corridor through the canyon was required. Travel by white water raft was the only practical way to meet this requirement. Accordingly, two river rafts, each capable of carrying four to five investigators with complete research and camping supplies for 2 weeks, were designed. Each boat consisted of two inflatable surplus bridge pontoons lashed catamaran style to a rigid aluminum frame (Fig. 2).

Sample design. Four consecutive summers (1978 to 1981) of sampling were required to examine the influence of both drought and rainfall periods on water quality. Summer is the popular season for river running. The research schedule included six, 2-week sample periods in 1978, two in 1979, and one each in 1980 and 1981.

To determine the effect of water level fluxes and the impact of tributary storm and nonstorm flows on water quality, both fixed-site and time-series samples were required. A fixed-site design was used in 1978 to establish location-specific profiles of river and tributary water quality. Forty-six river sites were located at recreation attraction sites, camping beaches, and at positions bracketing tributary confluences. River bottom sediments were collected at 20 of those sites. Except for river sediment and selected tributary bracketing sites, fixed sites on the river were eliminated in lieu of time-series samples during subsequent years. Fixed sites were also sampled on 26 tributaries in 1978, 13 tributaries in 1979, and 12 tributaries in both 1980 and 1981.

With an average flow rate of 8.3 km h^{-1}, Colorado River water has a travel time between Lee's Ferry and Diamond Creek of about 45 h. This fast, continual renewal of water in the river channel suggests that surface water quality may vary over short time intervals. Accordingly, time-series samples were collected (1978 to 1981) to detect these changes. Three samples were collected daily from the river at 0800, 1200, and 1800 h (at the location of the research rafts). These times were selected to monitor water quality through the daylight period, when float trips make principal use of river water. Because of overnight and sampling stops, the rafts traveled at a rate much slower than the current. Accordingly, samples collected at progressive time intervals were from new upstream units of stream flow.

Surface water samples were collected in sterile Whirl Pak bags from the top 15 cm of water. Samples were stored on ice until analysis, which was within 6 h (2). Bottom sediment samples were collected after surface water sampling. Sediments were taken from the top 5 cm of bottom material (1), within 0.50 m of the shoreline at a water depth of 15 cm. A 7-cm, open-trough scoop disinfected with 70% ethanol was used to collect sediments. Sediments were double bagged in sterile Whirl Pak bags and stored directly on ice until laboratory analyses could be done.

FC, TC, and FS concentrations in surface water samples were determined by membrane filtration (2). The field membrane-filtration system, designed for use in Grand Canyon, consisted of a high-volume Guzzler 400 boat bilge pump as a hand-powered vacuum source, a Millipore three-place manifold, Gelman magnetic filter funnels, and Gelman type GN-6 0.45-μm (pore size) presterilized membrane filters. Membrane filtration equipment was sterilized by 5-min exposure to UV germicidal lamps (2,537 nm) housed in a military radio

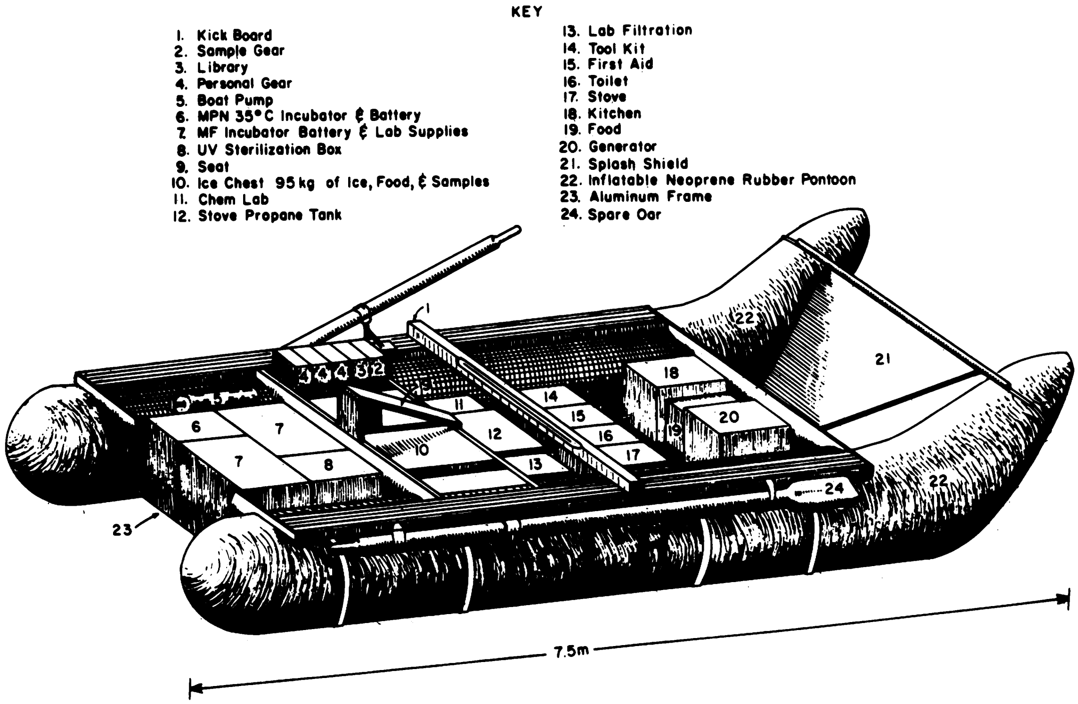

FIG. 2. Research raft with decks removed to expose inventory.

box equipped with a 12-V deep-cycle storage battery. Fresh media was prepared in the field from preweighed lots sealed in sterile airtight vials. FC, FS, and TC bacteria were detected using m-FC agar (Difco Laboratories, Detroit, Mich.), KF-streptococcus agar (BBL Microbiology Systems, Cockeysville, Md.), and M-Endo agar (BBL), respectively, in 47-mm Millipore petri dishes. Plates were incubated in Millipore aluminum block incubators that were individually housed in radio boxes equipped with 12-V batteries.

Turbidities in the Colorado River and tributaries were usually sufficiently low that interfering suspended sediment did not accumulate on filters. When sediment loads became excessive, filter volumes were split into smaller units, processed on separate filters, and counted collectively, e.g., a 100-ml filter volume became 4 × 25 ml or when necessary 10 × 10 ml (14). Turbidity measurements were made of each surface water sample with a Hach DR-EL colorimeter.

The most probable number method used for sediment analysis was not adaptable to field conditions in Grand Canyon. Sediment samples were stored on ice until they could be analyzed in a laboratory (5). Iced storage of sediments was tested by inoculating autoclaved, Colorado River bottom sediments with FC (640,000 FC 100 ml^{-1}). These sediments were divided into 100-ml lots and stored directly on ice for up to 21 days. After 1 full day of storage, 10 replicate sediment samples were removed from storage every other day for 21 days to determine residual FC densities. Based on means representing the 10 replicates for each storage length, no significant ($P > 0.05$) decline in FC densities was detected after 14 days, the longest field storage period required. All sediments were analyzed for FC by the method of Van Donsel and Geldriech (38), with the exception that sediments were measured and shaken in 250-ml graduated cylinders without the addition of glass beads.

RESULTS

The water quality status of the Colorado River and tributaries can be divided into three significantly different categories: nonstorm flow, storm flow, and bottom sediments. Although important relationships exist between these categories, they are presented separately here.

Nonstorm flow. The summers of 1978 to 1980 were marked by drought; consequently, the Colorado River and its tributaries were free of major storm flow during those years (Fig. 3). Log mean turbidities for the Colorado River were ≤16 nephelometric turbidity units through the drought period and mean and median FC densities were ≤2.4 FC 100 ml^{-1} (Table 1). Based on time series samples, FC concentrations during this period were ≤10 and ≤3 FC 100 ml^{-1} for 95% and 75% of the time, respectively. In only 3 of 443 samples did bacterial densities exceed FC 100 ml^{-1}. Of these three samples two, 245 and 1,165 FC 100 ml^{-1}, exceeded the recreational full-body contact standard of 200 FC 100 ml^{-1}. Both of these observations were associated with temporary, rain-induced turbidities of 100 nephelometric turbidity units.

The third peak observation, 120 FC 100 ml^{-1} occurred in conjunction with a turbidity of 99 nephelometric turbidity units which resulted from visible beach and bed scour within the Colorado River. Scour is particularly pronounced when river beaches, exposed during hydroelectric ebb flows, are eroded during peak flow releases. Notable beach scour occurred during nonstorm flow periods, but analysis of variance between FC densities at ebb and peak flows showed no significant increase ($P > 0.05$) in FC numbers during peak releases.

FC densities in tributaries were slightly more variable during 1978 to 1980 than in the river. Mean and median FC concentrations in tributaries were similar to those in the river (Table 1). Individual observations exceeded 10 FC 100

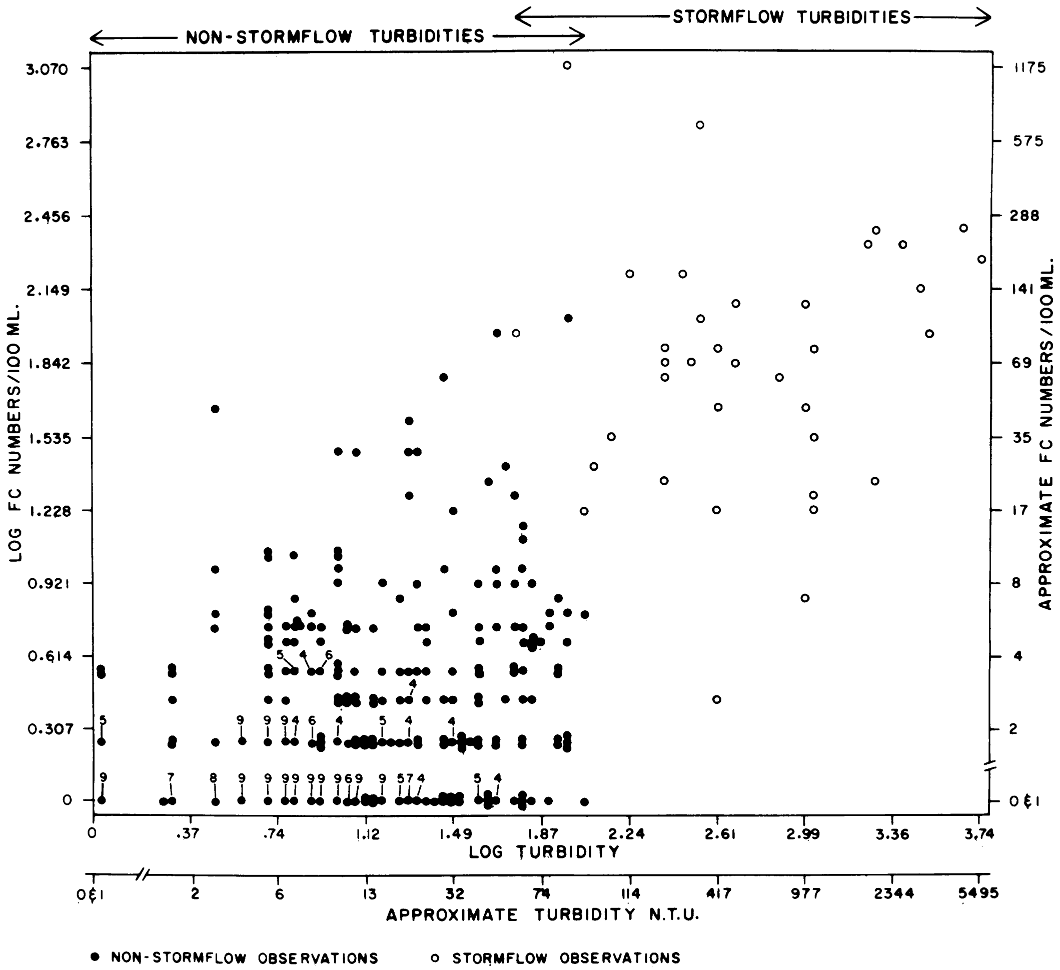

FIG. 3. Log_{10} FC per 100 ml versus log_{10} turbidity for 479 Colorado River water samples, 1978 to 1981.

ml^{-1} four times more often than in the river, but were ≤20 FC 100 ml^{-1} for 90% of the time. Tributaries generally carry low stream flow volumes during drought periods. This may subject them to temporary, but significant variations in FC densities due to direct fecal contamination or sediment disruption. Sediment disruption in tributaries may have significance for recreation. On 5 August 1979, Elves Chasm, a popular water play site for river trips, had 4,810 FC 100 ml^{-1} in the water and 9,200 FC 100 ml^{-1} in the sediments. Immediately before sampling, some 50 people had engaged in water play that disrupted sediments in the confined pools of the chasm. The second highest observation for this site was 120 FC 100 ml^{-1}.

Tributary bracketing samples did not show any tributary inflow impact on river water quality, even when relatively high FC densities were found in inflow waters. Apparently, the stream flow volume of the Colorado River so exceeded that of the tributaries that any input was diluted beyond detection.

Based on log means, neither the river nor its tributaries exceeded the full-body contact standard during 1978 to 1980 (Table 1). The 5 August 1979 observation at Elves Chasm was the highest FC density recorded in this period. Of the 26 tributaries examined, Hermit Creek, Elves Chasm, and Havasu Creek most frequently had FC concentrations above 100 FC 100 ml^{-1}. The Hermit and Elves Chasm watersheds are in natural states, but the stream courses are intensively used for water-based recreation. Havasu Creek drains the Havasupai Indian Reservation and the village of Supai and is also used intensively for recreation by backpackers and river runners.

In addition to recreation contact, Grand Canyon visitors also use the river and tributaries for drinking water. TC and FC data for 1978 to 1980 (Table 1) indicate that river and tributary waters consistently failed to meet drinking water standards (public law 93-523).

Because disposal of human sewage is carefully regulated, livestock grazing is excluded, and pack stock use is carefully restricted, wildlife are probably the most important source of fecal contamination during nonstorm flow periods. This contention is supported by FC:FS ratios that were consistently below 0.7 (Table 1) (15). These ratios cannot be considered reliable unless fecal deposition has occurred within 24 h of sampling (15). Hydrological movement from watershed surfaces to stream channels is completely absent during prolonged drought. Accordingly, fecal contamination of the river and tributaries must result from direct deposition in stream channels. Because of fast flow rates, stream waters have short residencies in Grand Canyon. Accordingly, there is a good probability that the ratios calculated herein are based on recent deposition.

Storm flow. In contrast to the summer droughts of 1978 to 1980, the summer of 1981 had a well-developed rainy season which generated turbid storm flows in both the Paria and

TABLE 1. Statistical values for selected water quality parameters for the Colorado River and tributaries, 1978 to 1981

Yr and stream[a]	Statistic	Water temp (°C)	pH	Water: Turbidity (NTU)	Water: TC (100 ml⁻¹)	Water: FC (100 ml⁻¹)	Water: FS (100 ml⁻¹)	Water: FC/FS ratio	Bottom sediments (FC 100 ml⁻¹)
1978									
Col R	Mean	12.9	8.1	16.0[b]		2.1[b]	63[b]	0.10[d]	110[b]
	Median	13	8.2	9		1	47		158
	n	410	153	360		338	85	27	83
Trib	Mean	21.6	8.3	4.2[b]		3.1[b]	63[b]	0.06[d]	203[b]
	Median	21	8.4	4		1	66		440
	n	178	67	154		189	44	14	138
1979									
Col R	Mean	11.6		11.0[b]		2.4[b]			51[b]
	Median	11		10		1			170
	n	73		71		69			14
Trib	Mean	21.3		7.5[b]		7.9[b]			2,188[b]
	Median	21		4		3.5			1,360
	n	26		26		26			14
1980									
Col R	Mean	11.6		7.8[b]	40[c]	1.4[b]	65[b]		135[b]
	Median	11		8	4	0	3		198
	n	36		35	10	36	10		8
Trib	Mean	21.8		7.9[b]	78[c]	4.4[b]	159[b]	0.02[d]	2,461[b]
	Median	22		8	53	8	200		3,940
	n	12		11	8	11	5	4	11
1981									
Col R	Mean	13.7		589.0[b]	453[c]	66.0[b]	324[b]	0.30[d]	155[b]
	Median	14		500	445	81	405		460
	n	38		37	8	36	8	8	7
Trib	Mean	23.3		32.0[b]	281[c]	45.0[b]			3,388[b]
	Median	23		16	380	19			4,800
	n	12		12	4	10			9

[a] Col R, Colorado River; Trib, tributary.
[b] Tabulated values = antilog (sum of log individual observations/*n* observations).
[c] Tabulated values = sum of individual observations/*n* observations.
[d] Tabulated values = (sum of individual FC values/individual FS values)/*n* observations, where FS density is >100 FS 100 ml^{-1}

Little Colorado Rivers. Colorado River turbidity and FC levels downstream of these tributaries were markedly higher than in previous years (Table 1 and Fig. 3). The close association between river FC densities and turbidities suggests that storm flow turbidity may be useful to model FC contamination (Fig. 4). River storm flow turbidities and FC densities were positively correlated, $r = 0.54$ ($P < 0.05$).

Individual samples from the Colorado River during the storm flow period exceeded the 200 FC 100 ml^{-1} standard (3, 41) with a frequency suggesting marginal full-body contact acceptability (Fig. 4). Storm flow observations of the Paria and Little Colorado Rivers clearly indicate that, at times, fecal contamination levels also exceeded acceptable contact limits.

Bottom sediment quality. In general, FC concentrations in river and tributary bottom sediments exceeded those of the water by 1.5 to 2.5 and 2.0 to 3.0 orders of magnitude, respectively (Fig. 5). These differences in FC concentrations are based on log means of all bottom sediment and water observations for each indicated research period. At selected river and tributary sites and sample times, differences between paired bottom sediment and water FC concentrations ranged from near equality to an excess of FC in sediments by a factor of nearly 48,000. This factor may have been greater, but the most probable number analyses used to examine sediments had an upper concentration limit of 48,000 FC 100 ml^{-1}. This limit was met 11 times out of 284 river and tributary samples.

Both the river and tributaries exhibited an increase in sediment FC densities over time for 1978 (Fig. 5). Data are not available for subsequent years to confirm annual replication of this pattern. Mean sediment FC concentration levels for the July and July to August periods were, however, similar for all years examined.

DISCUSSION

The highly ephemeral precipitation cycle characteristic of the arid Southwestern United States was the most important factor influencing recreational water quality in Grand Canyon. Based on 1978 to 1980 data, high-quality waters can be expected in the Colorado River and tributaries during drought portions of the cycle. In contrast, recreational water contact standards are likely to be exceeded during storm flows.

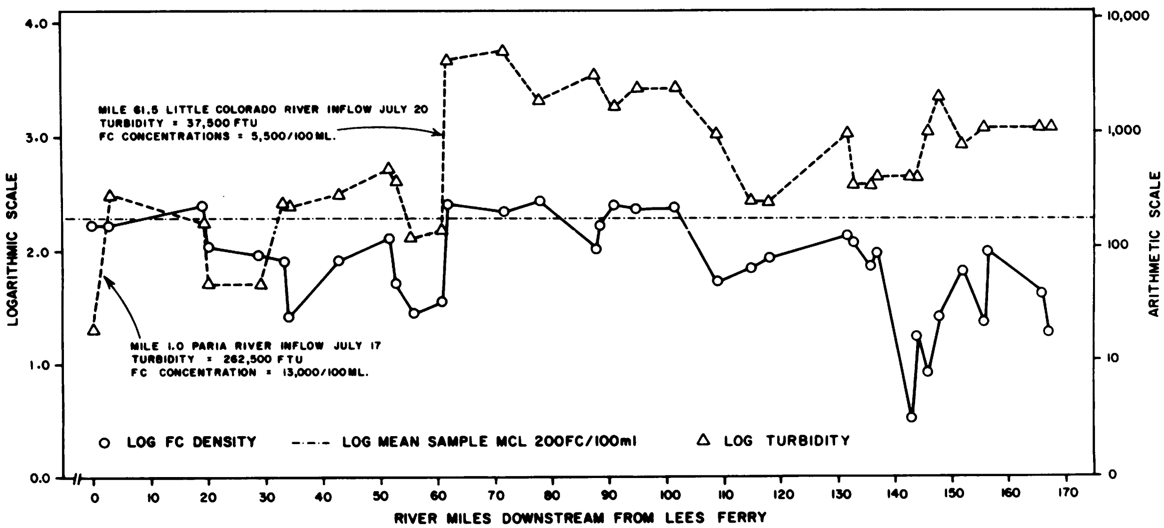

FIG. 4. FC densities and turbidities in the Colorado River, 1981. The impacts of Paria and Little Colorado River storm flow discharges on the Colorado River are evident at miles 1 and 61.5.

Drought periods. A highly consistent profile has been established for the river and tributaries during nonstorm flow periods. Based on this profile, concentrations of ≤ 10 and ≤ 20 FC 100 ml^{-1} in the river and tributaries, respectively, could be expected. These data established a baseline contamination level for Grand Canyon during drought and are comparable to those reported for high-quality mountain streams, in which FC densities were generally ≤ 20 FC 100 ml^{-1} (31, 39). TC densities in mountain streams have also been found to be similar to those in the canyon during the 1980 nonstorm flow period (31–33, 39). Although bacterial data indicate similarities between Grand Canyon waters and protected mountain streams, the canyon data reflects hydrological processes that differ sharply from humid mountain environments.

During drought, the hydrologically active (27) portions of the Grand Canyon watershed are strictly limited, for weeks to months, to the channels of the Colorado River and its few perennial tributaries. Mountain streams in humid environments are usually characterized by hydrologically active zones that exceed the limits of the stream channel. Flow from watershed surfaces to stream channels is frequent, but vegetation and soil litter act to stabilize soils and other debris, including fecal material, during all but major runoff events (10, 27). Accordingly, high-quality stream waters may be produced by dissimilar processes, prolonged absence of hydrological movement during drought in the arid environment and stabilization of erodable fecal material during hydrological movement in the humid setting.

Abrupt increases in stream stage height due to reservoir releases have been shown to increase downstream TC densities ca. 10-fold, as organisms deposited on stream banks between ebb and peak flow heights are suspended (24). Hydroelectric releases from Glen Canyon Dam caused daily stage changes of up to 3 m in the Colorado River. Although some high FC densities during nonstorm flow conditions could be associated with elevated turbidities resulting from beach scour, no significant correlations were found between FC densities and stage height or turbidity. Apparently, river banks are not sufficiently contaminated when exposed during ebb flows that water quality is appreciably degraded during peak flows. The steep narrow channel of the river within the canyon walls greatly restricts bank area accessible to wildlife. This, coupled with large-volume stream flows which dilute newly suspended contaminants, may be factors limiting measurable contamination during stream stage increase.

Rainfall periods. Arid environments such as Grand Canyon are susceptible to flash floods due to intense rainfall over sparsely vegetated watersheds with extremely steep slopes which have exposed bedrock and impermeable soils. With the onset of sufficient rainfall, the hydrologically active portion of a desert watershed may expand quickly from near zero to include most of the basin. Because considerable fecal debris may have accumulated on watersheds between ephemeral storm events, highly contaminated storm flows may result. In contrast, storm runoff rates in humid vegetative environments are retarded by vegetative cover, soil litter, and soil infiltration rates, reducing both hydrograph peaks and runoff volume. Accordingly, rainfall events of equal magnitude may have the potential to cause greater peak nonpoint-source fecal loading of streams in arid lands than they do in humid settings.

The impact of storm events on Colorado River water quality will vary considerably depending on the portion of the watershed generating storm flow, the volume generated, and the flow volume of the river available to dilute the storm flow input. Storm flow in 1981 persisted for weeks as a result of scattered but frequent thunderstorms over the Paria and Little Colorado River basins. Collectively, these storms maintained continuous discharge into the Colorado River. By virtue of flow volume, the Little Colorado River was the major contributor of Colorado River turbidity and FC below the confluence of these two rivers (Fig. 4). Historically, the Little Colorado River is the major source of storm flow in the Colorado River (35). Annual stream flow in the Little Colorado is 8 and 35.4 times that of the Paria River and Kanab Creek, respectively. All three tributaries are dominated by storm flow events (35). The 1981 storm events produced slightly below average storm flows in the Paria and Little Colorado Rivers, 8.6 and 26 m^3 s^{-1}, respectively. Storm flow events up to 456 and 3,400 m^3 s^{-1} for the Paria and Little Colorado Rivers, respectively, have occurred (35). Presumably, the volume and concentration of fecal

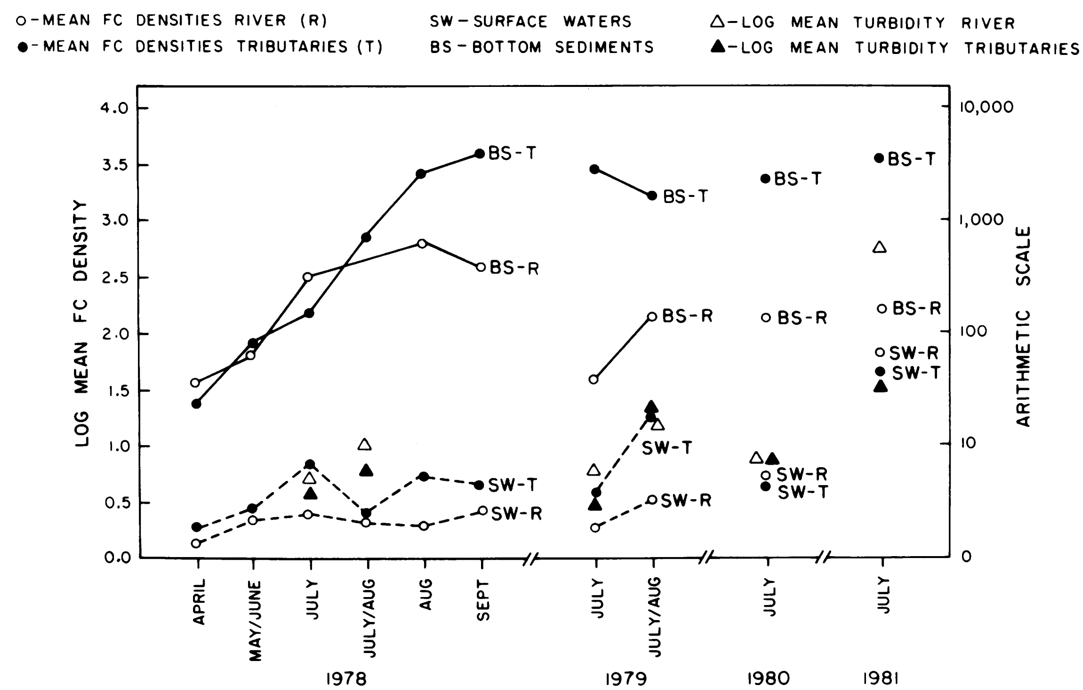

FIG. 5. Log_{10} mean FC densities by research float trip in the waters and bottom sediments of the Colorado River and tributaries, 1978 to 1981. Log_{10} turbidities by research trip are also shown.

contaminants in storm flow will increase with runoff volume, especially in arid environments.

The Colorado River exceeded full-body contact standards only during storm flows. Previous studies had not provided an indication that fecal contamination due to storm flows in pristine wild lands would reach the magnitude observed in Grand Canyon (31–33, 39). Although storm flows exceeded contact standards, actual health risks associated with recreational waters could not be reliably estimated because of deficiencies associated with the FC standard (7). Changes in the standards have been proposed which would link health risks related to water-based recreation directly with evidence linking water contact with rates of gastrointestinal disease, by using *Escherichia coli* and enterococci as indicator bacteria (8, 12). For Grand Canyon and other wild land settings, the proposed standards may not be an improvement. Assuming that wildlife and livestock are the principal sources of fecal contamination in wild lands, waterborne disease hazards must be related to disease rates among these animals. Because the proposed standards are currently based on epidemiological studies of beaches in the eastern United States contaminated with sewage effluents from point sources, they may not be appropriate for western wild land settings where nonpoint source contamination predominates. An appropriate approach for these wild land areas would be to examine relationships between indicator bacteria and pathogen occurrence in waters and disease incidence rates among users of these recreational waters.

Turbidity. Because access to the Colorado River is difficult, routine water quality monitoring by the NPS is not easily accomplished. The 1981 storm flow pattern suggests that turbidity may be a useful tool to quantitatively model FC loading (Fig. 4). Although a positive correlation (r = 0.54) between turbidity and FC densities was found, only ca. 29% of the variance (r^2 = 0.29) in FC can be explained by storm flow turbidity. The strength of this relationship suggests that a turbidity model could only be used to predict general levels of FC loading. More extensive monitoring, as suggested by Thornton et al. (34), may improve the potential of this model. Additionally, stream flow volume is a second parameter that may assist in developing a modeling tool for Grand Canyon. Perrier et al. (28) initially found an r^2 value of only 0.19 when trying to predict coliform loading as a function of stream flow on the Caddo River. This relationship improved to 0.42 when only the rising leg of the storm flow hydrograph was examined. The rising leg more clearly isolates the impact of the more contaminated first flush flows (11). By monitoring storm flow values, FC loadings, and turbidities at points accessible to vehicles on the Paria and Little Colorado Rivers before they discharge into the Grand Canyon, storm flow water quality in the Colorado River may be predictable.

Bottom sediments and overlying waters. Mean FC densities in river and tributary sediments in 1978 through 1980 were in excess of 10- to 1,000-fold of those in overlying waters, a pattern that reflects findings from other environments (17, 18, 23, 39). That FC densities in sediments would exceed those in water by a wide margin was somewhat surprising during extended nonstorm flow periods, considering the high quality of surface waters. The processes which determine the distributions of FC and, presumably, other enteric microorganisms in river and tributary waters and sediments are not specifically known but may be illustrated somewhat by the pattern that appeared in 1978.

Log mean FC densities in river and tributary sediments increased through the summer season, whereas those in the water column remained at a constant low level (Fig. 5). This suggests, as proposed by Hendricks (19), that FC in river and tributary sediments were able to persist for extended periods, whereas their densities increased by slow but steady addition from the overlying water. The basal nutrients and stable microhabitat that supposedly extends bacterial persistence in sediments may also promote reproduction, leading to concentration increases (19, 20). The probability of FC reproduction in Colorado River sediments was considered small, as water temperatures were low (8 to 12°C) and were near the minimum (7.5°C) found for coliform metabolism (30), and the mean sediment composition was 94% sand and 6% silt and clay, suggesting low organic matter concentrations (22).

Concentrations of FC in bottom sediments may have been augmented by stream-flow characteristics of the Colorado River. Hydroelectric fluctuations are greater in summer months than in other seasons. Water inundating beaches on peak flows drains through beach sands as the stream flow ebbs. This inundation-drainage process possibly allows sand filtration of FC from the water column much like that which occurs in water treatment facilities (9, 26). FC have been found to persist in moist Colorado River beach sands for several days to weeks (29). The combined effect of sand filtration an extended persistence may gradually concentrate FC bacteria in the sediments.

Bottom roughness and shallow water depths in tributaries promote significant flow interaction between bottom sediments and stream water (21). Interflow processes in the sediments could also lead to retention of bacteria from the water column through a filter-like process.

Mean FC densities in river sediments were only 2.3 times those in the overlying waters in 1981. Based on elevated FC densities found in overlying waters, an increase in sediment FC densities might have been expected, but 1981 sediments remained on a par with levels found in previous years (Fig. 5). Mechanisms which would account for these water-sediment FC interactions in Grand Canyon remain undetermined.

FC densities in bottom sediments have been suggested as a more stable index of overall water quality than those of the overlying water (19, 38). Findings for Grand Canyon do not support this contention. Neither the data for 1978, which showed a seasonal accumulation of FC in bottom sediments, nor the storm flow data for 1981 reflect any indexing relationship between FC densities in bottom sediments and water. These environments obviously interact but apparently do so in a manner which does not allow FC densities in one to predict or index those in the other in either a general or specific manner. Based on canyon data, overall water quality can be determined only by monitoring both sediments and water to determine the respective significance of each.

Management. The findings of this study have served as the basis for new public information and education efforts by the NPS at Grand Canyon. Special emphasis has been placed on proper water treatment application by river runners and hikers. Previously many groups ignored concerns for health risks and drank both nonstorm flow and storm flow waters in the canyon without treatment. For the first time, the NPS and river runners are also aware that sediments and storm flows significantly contribute to water contamination. Storm flow turbidity, visually distinguishable in Grand Canyon from resuspension turbidity, is being used as an indicator of elevated contamination levels and possible contact hazards.

This work also demonstrates the importance of ephemeral rainfall in inducing nonpoint-source fecal contamination in pristine desert streams and rivers. In addition, the sediments of these high-quality stream waters have been found to harbor elevated concentrations of enteric bacteria in a pattern similar to that long established for more polluted waterways. Finally, this research has demonstrated that remote backcountry waters which are inaccessible by vehicle can be monitored on a wide scale for various microbiological parameters.

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LITERATURE CITED

1. **Allen, I. A., J. Grindley, and E. Brooks.** 1953. Some chemical and bacterial characteristics of bottom deposits from lakes and estuaries. J. Hyg. **51**:185–194.
2. **American Public Health Association.** 1980. Standard method for the examination of water and wastewater, 15th ed. American Public Health Association, Inc., Washington, D.C.
3. **Arizona Compilation of Rules and Regulations.** 1980. R, 9-21-209. Department of State. Phoenix, Ariz.
4. **Brickler, S. K., R. Motschall, and R. Phillips.** 1976. A water quality analysis of recreation waters in Sabino Canyon. Coronado National Forest on Cooperative Agreement 03-05-01-75. University of Arizona, Tucson.
5. **Brickler, S. K., and B. Tunnicliff.** 1980. Water quality analysis of the Colorado River corridor of Grand Canyon. College of Agriculture paper 350. University of Arizona, Tucson.
6. **Bissonnette, G. K., D. G. Stuart, T. D. Goodrich, and W. G. Walter.** 1970. Preliminary studies of serological types of enterobacteria occurring in a closed mountain watershed. Proc. Mont. Acad. Sci. **30**:66–76.
7. **Cabelli, V.** 1982. Microbial indicator systems for assessing water quality. Antonie van Leeuwenhoek **48**:613–618.
8. **Cabelli, V. J.** 1983. Health effects criteria for marine recreational waters. Publication no. EPA-600/1-80-031. U.S. Environmental Protection Agency, Washington, D.C.
9. **Chambers, C. W., and N. A. Clarke.** 1966. Control of bacteria in nondomestic water supplies, p. 105–139. *In* W. E. Umbreit (ed.), Advances in applied microbiology. Academic Press, Inc., New York.
10. **Cummins, K. W., J. R. Sedell, F. J. Swanson, G. W. Minshall, S. G. Fisher, C. E. Cushing, R. C. Peterson, and R. L. Vannote.** 1983. Organic matter budgets for stream ecosystems: problems in their evaluation, p. 299–353. *In* Stream ecology: application and testing of general ecological theory. Plenum Publishing Corp., New York.
11. **Davis, E. M., D. M. Casserly, and J. D. Moore.** 1977. Bacterial relationships in stormwaters. Water Resour. Bull. **13**:895–905.
12. **Dufour, A. P.** 1982. Fresh recreational water quality and swimming-associated illness. Second National Symposium on Municipal Wastewater Disinfection, Orlando, Florida.
13. **Fair, J. F., and S. M. Morrison.** 1967. Recovery of bacterial pathogens from high quality surface water. Water Resour. Res. **3**:799–803.

13a. **Federal Water Pollution Control Administration.** 1968. Water quality criteria. U.S. Government Printing Office, Washington, D.C.

14. **Geldreich, E. E.** 1975. Handbook for evaluating water bacteriological laboratories, p. 126. Publication no. EPA-670/9-75-006. U.S. Environmental Protection Agency, Washington, D.C.
15. **Geldreich, E. E.** 1976. Fecal coliform and fecal streptococcus density relationships in waste discharges and receiving waters. Crit. Rev. Environ. Control **6**:349–368.
16. **Geldreich, E. E., H. F. Clark, and C. B. Huff.** 1964. A study of pollution indicators in a waste stabilization pond. J. Water Pollut. Control Fed. **36**:1372.
17. **Grimes, D. J.** 1980. Bacteriological water quality effects of hydraulically dredging contaminated Upper Mississippi River bottom sediment. Appl. Environ. Microbiol. **39**:782–789.

18. **Hendricks, C. W.** 1971. Increased recovery rate of salmonellae from stream bottom sediments versus surface water. Appl. Microbiol. **21**:379–380.
19. **Hendricks, C. W.** 1971. Enteric bacterial degradation of stream detritus. Water pollution control research series Project no. 16050 EQS. U.S. Environmental Protection Agency, Washington, D.C.
20. **Hendricks, C. W., and S. M. Morrison.** 1967. Multiplication and growth of selected enteric bacteria in clear mountain stream water. Water Res. **1**:567–576.
21. **Hynes, H. B. N.** 1972. The ecology of running waters. University of Toronto Press.
22. **LaLiberte, P., and D. J. Grimes.** 1982. Survival of *Escherichia coli* in lake bottom sediment. Appl. Environ. Microbiol. **33**:623–628.
23. **Matson, F. A., S. G. Hornor, and J. D. Buck.** 1978. Pollution indicators and other microorganisms in river sediment. J. Water Pollut. Control Fed. **50**:13–19.
24. **McDonald, A., D. Kay, and A. Jenkins.** 1982. Generation of fecal and total coliform surges by stream flow manipulation in the absence of normal hydrometeorological stimuli. Appl. Environ. Microbiol. **44**:292–300.
25. **Merson, M. H., D. A. Goldmann, K. M. Boyer, N. J. Peterson, C. Patton, L. G. Everett, H. Downs, A. Steckler, and W. H. Barker, Jr.** 1974. An outbreak of *Shigella sonnei* gastroenteritis on Colorado River raft trips. Am. J. Epidemiol. **100**:186–196.
26. **Moore, B.** 1959. Sewage contamination of coastal bathing waters in England and Wales. J. Hyg. **57**:435–472.
27. **Novotny, V., and G. Chesters.** 1981. Handbook of nonpoint pollution: sources and management. Van Nostrand Reinhold, New York.
28. **Perrier, E. R., H. E. Werterdahl, and J. F. Nix.** 1977. Water quality loadings during thirteen storms on the Caddo River, Arkansas. American Society Agricultural Engineers Meeting, paper no. 77-2529.
29. **Phillips, R. A., and C. S. Lynch.** 1977. Human waste disposal on beaches of the Colorado River in Grand Canyon. Technical report II. Colorado River research program, Grand Canyon National Park, Az.
30. **Shaw, M. K., A. G. Marr, and J. L. Ingraham.** 1971. Determination of the minimum temperature for growth of *Escherichia coli*. J. Bacteriol. **105**:683–684.
31. **Skinner, Q. D., J. C. Adams, P. A. Rechard, and A. A. Beetle.** 1974. Effect of summer use of a mountain watershed on bacterial water quality. J. Environ. Qual. **3**:329–335.
32. **Stuart, D. G., G. K. Bissonnette, T. D. Goodrich, and W. G. Walter.** 1971. Effects of multiple use on water quality of high-mountain watersheds: bacteriological investigations of mountain streams. Appl. Microbiol. **22**:1048–1054.
33. **Stuart, S. A., G. A. McFeters, J. E. Schillinger, and D. G. Stuart.** 1976. Aquatic indicator bacteria in the high alpine zone. Appl. Environ. Microbiol. **31**:163–167.
34. **Thornton, K. W., J. F. Nix, and J. D. Bragg.** 1980. Coliforms and water quality: use of data in project design and operation. Water Res. Bull. **16**:86–92.
35. **U.S. Geological Survey.** 1980. Water resource data for Arizona. U.S. Geological Survey water data report. AZ-80-1. U.S. Geological Survey, Reston, Va.
36. **U.S. National Park Service.** 1979. Colorado river management plan, Grand Canyon National Park. Grand Canyon National Park, Az.
37. **U.S. Public Health Service.** 1980. Shigellosis among participants of Colorado River raft trips in Arizona, 1979. (unpublished administrative report, EPI-79-81-2) Centers for Disease Control, Atlanta, Ga.
38. **Van Donsel, D. J., and E. E. Geldreich.** 1971. Relationships of Salmonella to fecal coliforms in bottom sediments. Water Res. **5**:1079–1087.
39. **Varness, K. J., R. E. Pacha, and R. F. Lapen.** 1978. Effects of dispersed recreational activities on the microbiological quality of forest surface water. Appl. Environ. Microbiol. **38**:95–104.
40. **Walter, W. G., and R. P. Bottman.** 1967. Microbiological and chemical studies of an open and a closed watershed. J. Environ. Health **39**:157–163.